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RESEARCH IN LONG HOLE EXPLORATORY DRILLING FOR RAPID EXCAVATION UNDERGROUND

Thomas N. Williamson

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RESEARCH IN LONG HOLE EXPLORATORY DRILLING FOR RAPID EXCAVATION UNDERGROUND

Prepared For

U. S. BUREAU OF MINES

FINAL REPORT – PHASE II

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13. ABSTRACT

A method of drilling 1000 foot deep exploratory holes from a tunnel was tested in three quarries. Design data was taken for development of a drill to make a four inch diameter hole underground in moderately strong and high strength rock. A system combining diamond drilling and in-hole percussion drill was successful.

Test results showed that the system should be capable of 90 feet of hole per shift in high strength granite and over 150 feet per shift in moderately strong dolomite. A new combination of systems for handling 1000 feet of drill rod entact in a storage pipe and circulating drilling fluid through that storage pipe was very successful. Success was also achieved in handling and preventing some rod failures and in overcoming problems of losses of drilling fluid to the formation. Hole direction problems beyond 300 feet have not been completely solved.

Penetration rates of 70 ft. per hour were obtained with a down hole percussion drill in dolomite and 30 ft. per hour in strong granite. This method should be perfected with a moderate amount of additional research and be ready for field use with one year after that additional research is started.

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Horizontal Drilling						

FINAL REPORT - PHASE II

RESEARCH IN LONG-HOLE EXPLORATORY DRILLING for EXCAVATION UNDERGROUND

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3.0 TECHNICAL SUMMARY

There are prospects for tremendous growth in demand for excavation for civilian and military public works underground during the rest of this century. A tool which is currently being developed will play a significant role in the need, particularly in moderate strength and high strength rock. This tool is the tunnel boring machine.

Tunnel boring machines have been used to drill tunnels from 8 ft. to over 30 ft. in diameter in rock of 10,000 to over 30,000 psi unconfined compressive strength. This includes most of the common sedimentary, metamorphic and igneous rocks such as sandstones, limestones, shales, granites and schists. These boring machines often advance at more than double the rate made by conventional tunnel driving techniques with about one third the people in the dangerous tunnel face area.

While tunnel boring machines have increased speed, efficiency and safety of this kind of excavation, they have introduced some potential new hazards to safety and prospects for some increase in cost because of their high speed. They must advance so fast to justify the increased capital cost that there is the possibility of rapidly penetrating a changed geological condition which could be costly in safety, time or costs.

This research project directs itself to providing a means to probe ahead of a tunnel boring machine with a 4 in. diameter hole 1000 ft. deep. This would be the smallest diameter compatible with drilling tools available or likely to be available soon and the depth capability would provide three or four days warning of water, gas or bad roof conditions. The probe hole drilling must be done rapidly to avoid delaying the tunnelling process.

The particular phase of the research program, covered in this report, was the testing of hardware conceived and assembled in prior work to accomplish this probe hole drilling. Test drilling was conducted at quarries in California with rock of moderate and high strength.

Three candidate drilling methods were tried including rolling cutter bits, commonly used in oil wells, diamond bits and percussion drilling. It was recognized early that diamonds would be required for occasional retrieval of solid rock samples, or cores, but that higher speed percussion drills must be used to obtain the high production rates required. Down hole percussion drills penetrate the hardest rock at 30 fph or five times as fast as diamond drills. They can drill moderate strength rock twice as fast as high strength rock or at 60 fph.

A novel method of handling 1000 ft. of drill rod in one piece, in a tunnel and a new method of circulating drilling fluid of air or water into this rod were conceived and tried successful in this program. Special tools have been designed and tested here which will insert or withdraw drill rod at an unprecedented rate of over 200 fpm. Details of the tests are described in this report and from these details it is quite obvious that a probing system can be developed which will permit drilling of 4 in. horizontal holes at 90 ft. per shift in high strength rock and over 150 ft. in moderate strength rock. These production rates include taking core samples at about 50 ft. intervals.

Nearly all the technical problems have been overcome and data gathered to design an ultimate system for tunneling. Problems solved include: bit planning; establishing power requirements; solution of circulation flow problems for cuttings removal; drill rod problems of prevention of unscrewing as well as retrieving broken rods; freeing stuck tools; establishing production criteria and prevention of loss of drilling fluid to broken formations. Problems continuing, for which several potential solutions are under study, are: methods to keep the probe hole straight; and methods to prevent overheating of hydraulic circuits.

4.0 PURPOSE

The primary purpose of this Phase II of a proposed three phase research effort is the creation of dependable probe hole drilling machines (PHDM) to be used primarily with a tunneling boring machine (TBM).

The effort is directed particularly to the use of such TBM's and PHDM's in high strength rock (HSR) and moderate strength rock (MSR). HSR has been defined for this study as that rock which has an unconfined compressive strength between 20,000 and 30,000 psi. MSR is that rock with a strength of 10,000 to 20,000 psi.

The last two decades (1950 to 1970) provided a tremendous increase in TBM performance. (1)* This was particularly true in MSR. At the beginning of the 1970 decade the influence of this new method was beginning to be felt more strongly in HSR.

In good conditions TBM's can make 200 ft. per 3 shift day in MSR and about half of that in HSR. Their very high advance rates provide several problems to the contractor, owner and worker. These difficulties, in rapid advance, primarily are the result of penetrating very fast and deep into a dangerous rock or geological situation without forewarning. Dangerous geological situations can be bad roof or heavy water or gas inflows.

The purpose of probe hole research is to provide a drill that will be able to put a hole of about 3 to 5 in. diameter approximately 1000 ft. in advance of the TBM. It should be rapidly achieved and a goal has been set to produce such a probe hole 168 ft. per shift in MSR and 90 ft. per shift in HSR. These goals were set after a careful analysis of probable results and needs. Among these needs are the ability, in some situations, to make as much hole in six shifts with the probe drill (for example on a weekend) as the TBM is likely to make in five days of three shifts in each of the two kinds of rock under consideration. Another factor in the goal was that the drill would be capable of taking a reasonable core sample at required intervals. For this project these depth intervals were each set at 50 ft. or more frequently if a change in drilling rate or drilling conditions indicated a significant variation in geology which would indicate the need for such a more frequent sample.

The PHDM developed must be small, or require no more than about 4 ft. x 5ft. of tunnel cross section. The PHDM must also be capable of working in a damp atmosphere. It must be explosion proof and not create dust or noxious gas. The drill should be capable of being operated by two men.

*Note - Numbers alone in parenthesis-please refer to bibleography

5.0 TESTING FACILITIES

5.1 Drilling Systems Tested

An earlier research effort analyzed the state of the art for small hole-long horizontal drills which might be used for the purposes described in Section 4.0 to provide data for design of a probe drill. The conception and selection of equipment and method was described in some detail in an earlier study. (9)

Drilling methods selected for these tests were:

1. Rotary drilling with rolling cutter bits.
2. Rotary drilling with diamond core bits.
3. Down-hole percussion drills.

The plan was to test each of these three chosen drilling candidate methods in rock in at least two quarries representing MSR and HSR. Equipment was purchased to accomplish these tests and to use the new drilling system conceived in Phase I, (2), and is described briefly in Section 5.2 below.

It was recognized in Phase I that handling of drill rod would be the restraining element, unless wire line coring would prove to be the superior method for all of the drilling. This seemed unlikely, or at least there appeared to be a need to provide an alternative for this research program. An alternative drilling method was conceived and that is to store 1000 ft. of drill rod, permanently connected in full length, except for the tools on the front end. This rod is stored in a pipe or a previously drilled hole in back of the drill into which the rod is thrust when it is pulled from the hole being drilled.

5.2 Test Equipment

Pulling long drill rod sections through the drill requires a hollow spindle drilling machine shown in figure 5.1. This type of machine grips, rotates and forces the drill rod forward through itself by action of a chuck on round drill rod. This is representative of a proven type of diamond rotary drill available from several sources. By opening the chuck, the 1000 ft. of drill rod can be pulled through the drill into the storage pipe or hole very rapidly by a separate device. A special device was designed to perfom this. This extractor consists of two vertically movable wheels with grooves and these driven wheels move together to grip the rod or apart to release it, as is seen in Figure 5.2. These wheels are powered by a 18 HP hydraulic motor and the upper wheel is driven and synchronized to the lower by a chain drive. They were designed to drive the 1000 ft. of rod into or out of the hole at the rate of 200 ft. per minute.

The drill rod was stored in 1000 ft. of casing for the quarry tests in this effort, views of which are shown in figures 5.3 and 5.4. Note that the storage pipe was layed in a long gentle curve which shows that the system will work in a curved tunnel. The rear, or

HOLLOW SPINDLE ROTARY DRILL

FIG. 5.1

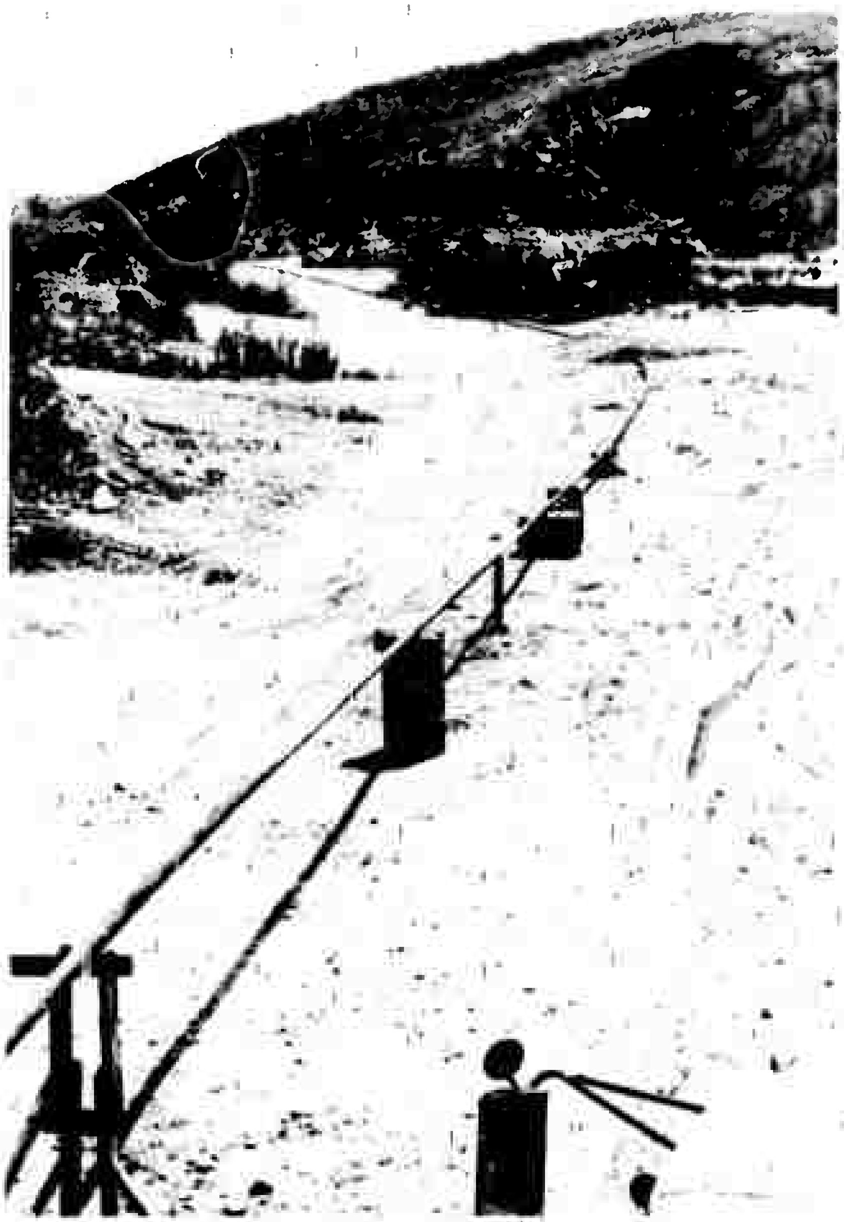
JACOB'S ROD EXTRACTOR

FIG. 5.2

STORAGE PIPE – RIVERSIDE

STORAGE PIPE AND RIG

FIG. 5.3



STORAGE PIPE FROM RIG

FIG. 5.4

outer end, of this storage pipe is plugged to retain the fluid. The storage pipe becomes a part of the drilling fluid circulation system. At the front end of the storage pipe, or that end near the drill, there is a stuffing box, shown in Figure 5.5. This contains the fluid in the storage pipe under pressure, at that end, whether this fluid is air or water. The stuffing box also allows the stored drill rod to rotate in the storage pipe to be inserted or withdrawn from it without leakage. A pipe tee at the stuffing box provides an entrance for the drill fluid to the storage pipe having been delivered to the tee from the compressor or pump as the case may be. The end of the drill rod which is in the storage pipe is open so that this fluid enters it and circulates through it and the tools into the hole annulus carrying the cuttings out in the normal way.

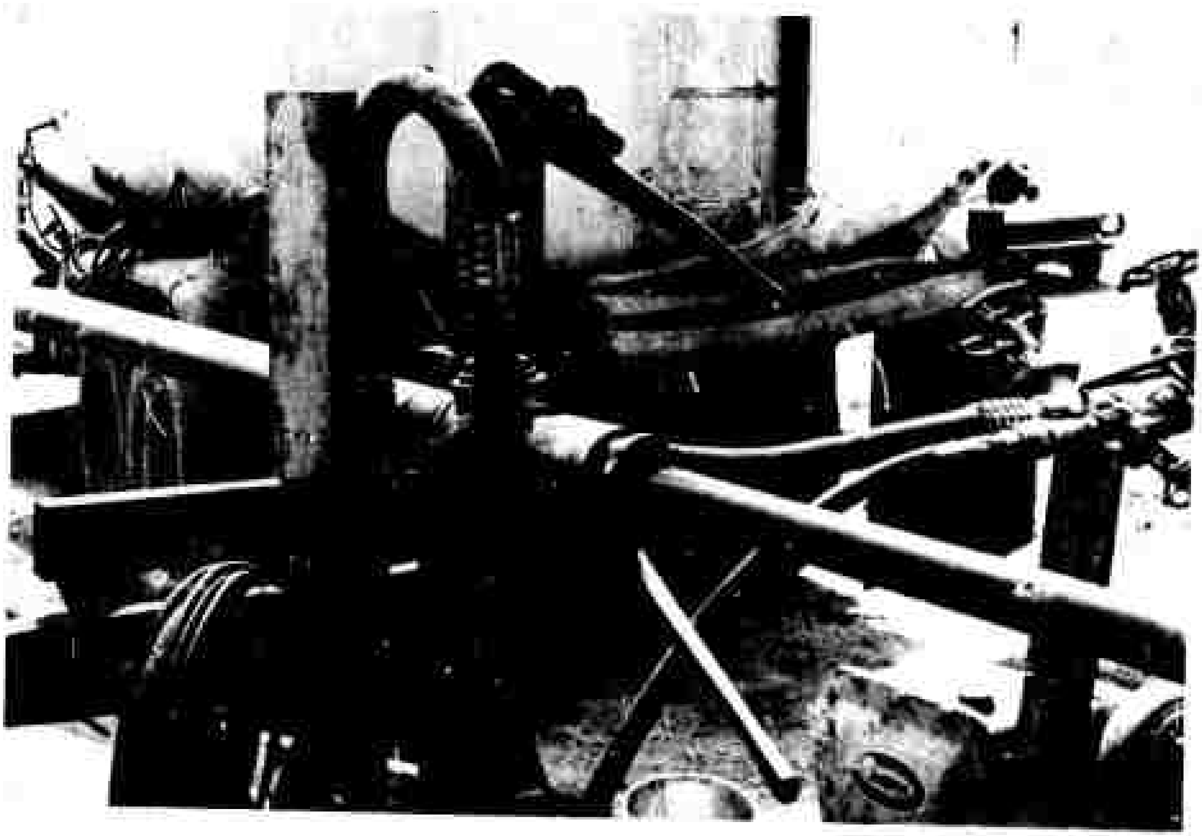
A short piece of surface casing of 2 to 4 ft. length is set in an oversized hole at the collar of the hole and it also has a stuffing box and tee. The returning fluid with cuttings is removed through this forward tee and the cuttings are separated in appropriate settling basins or dust collectors. These circulation schemes are shown diagramatically in Figures 5.6 and 5.7.

The drill was skid mounted with a swivel head and had a 2 ft. stroke. It is driven by a 35HP gasoline engine through a 4 speed transmission with a range of from 30 to 1000 rpm. The drill has an hydraulically actuated in and out movement on the skids which was useful in lining up with the holes. The drill was equipped with a fairly recently developed automatic chuck which cuts much time and labor from each stroke. A special feature of this drill was the inclusion of a hydraulic pump and drive between the engine and the gear box. It was recognized that such a drive might be necessary for the streamlining requirements of the ultimate PHDM. In the tunnel it may be desirable to have the power unit as a package and to have it separated from the drill because of lack of lateral space.

The drill rod is "B" wire line rod which is 2-3/8 in. flush OD and 1-13/16 in. flush ID and weighs 4 lb. per ft. It has 3 threads per in. and contains 13.4 gallons per 100 ft. The casing is "N" 3-1/2 in. OD and 3-3/16 in. ID. The stuffing boxes are those for "B" rod with reducers provided to connect them to the "N" casing and the larger surface pipe used in the hole collar. The hole collar pipe is 5 in. ID and was provided with a Victualic coupling for quick removal of the stuffing box when larger tools were withdrawn or inserted.

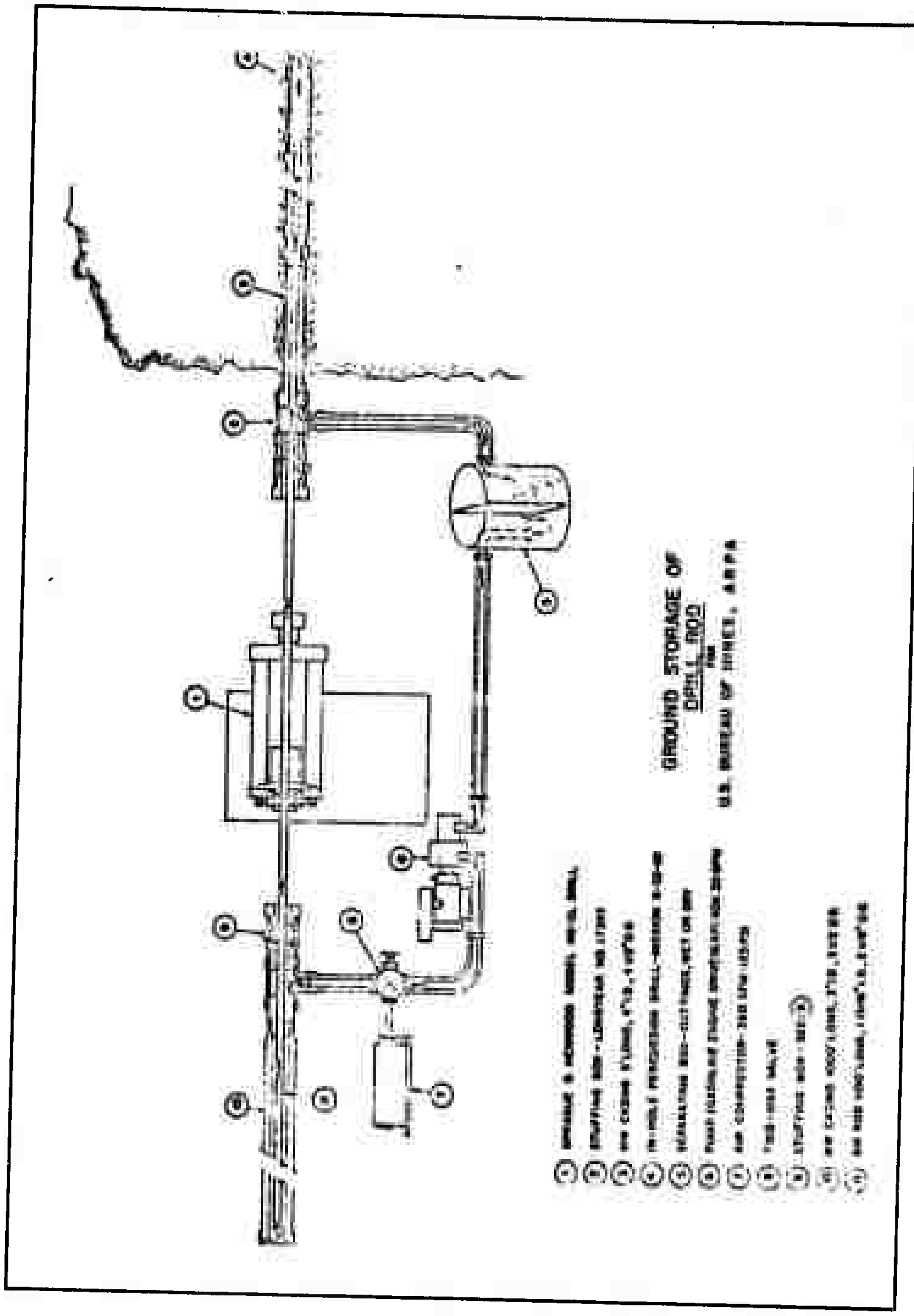
A Piston type water pump driven with gasoline engine pumped water at up to 30 gpm and 300 psi. Air compressors were rented locally as required. After trying 300 and 450 cfm the choice was a 600 cfm unit and all were run at 90 to 110 psi.

The down hole percussion drill, in Figure 5.8, is designed to drill a 4 or 4-1/2 in. hole. It is a 3-1/2 in. diameter tool about 40 in. long. It requires 300 cfm at 100 psi but the larger volume of 600 cfm was used for better hole cleaning. Percussion tools bits with cylindrical sintered tungsten carbide inserts were used.



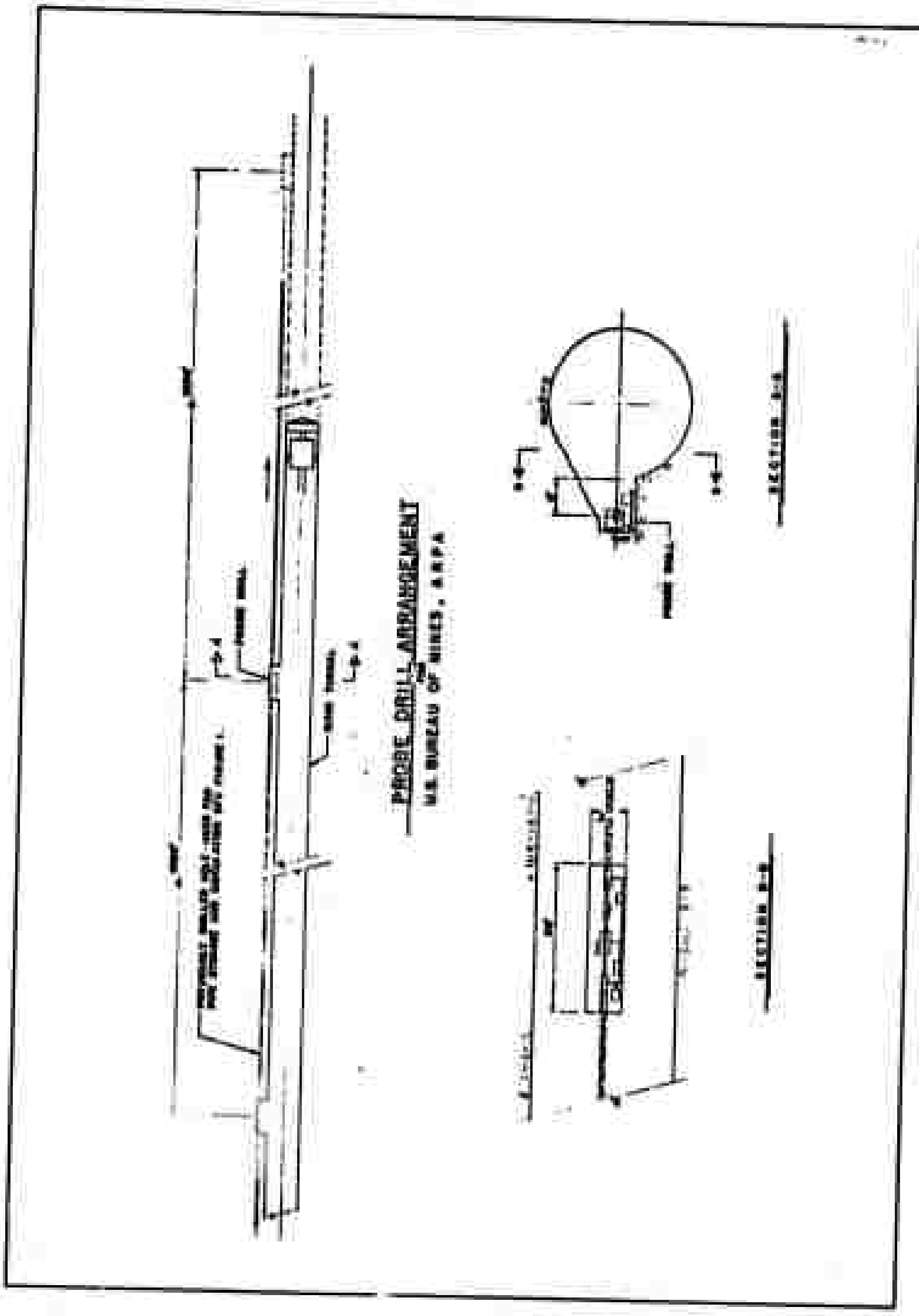
STORAGE PIPE STUFFING BOX

FIG. 5.5



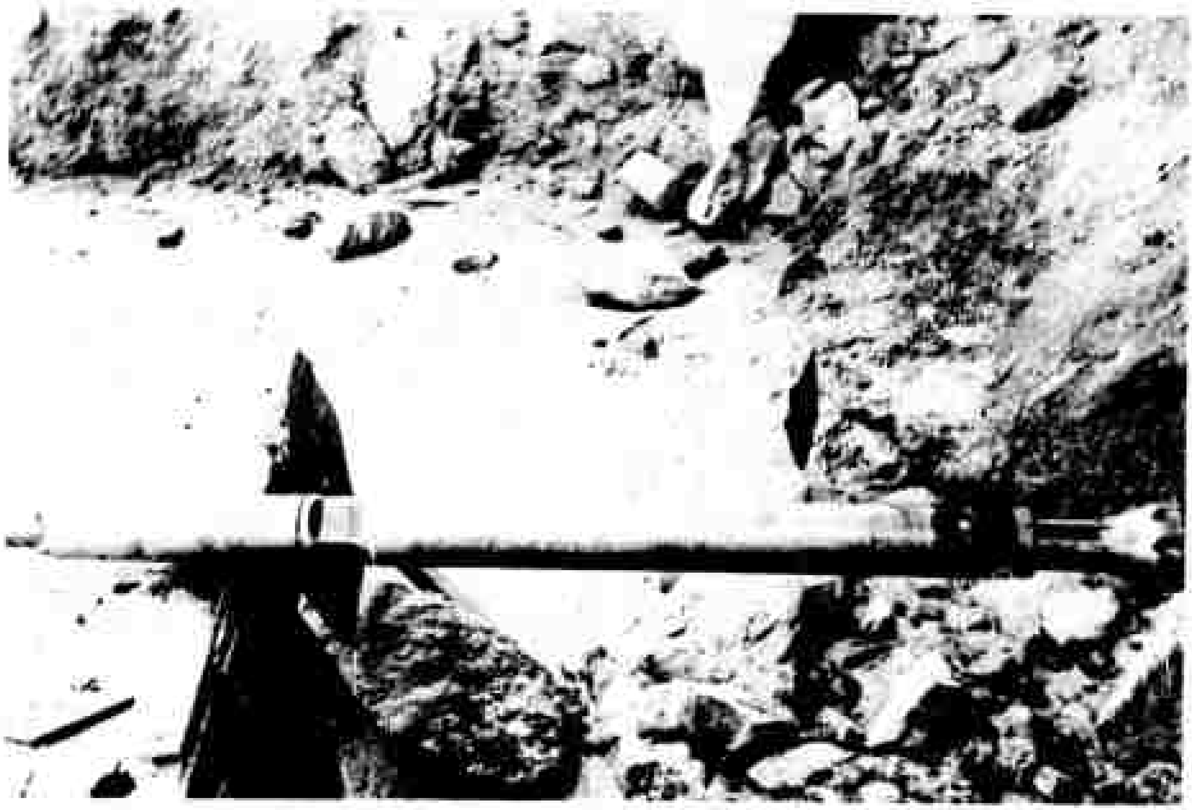
REAR ROD STORAGE AND
FLUID CIRCULATION SYSTEM

FIG. 5.6



DRILL ALCOVE MOUNTING IN TUNNEL

FIG. 5.7



DOWN HOLE PERCUSSION DRILL

FIG. 5.8

At one point a larger down hole percussion drill was used for a short test drilling a 5-1/2 in. diameter hole. Its performance was impressive. The larger hole could be drilled as fast as the smaller hole but would probably have led to more hole cleaning and directional problems.

Several types of diamond bits were used with no significant findings on types. Standard off the shelf industrial hard formation 3 cone steel toothed bits were used.

Two oil field type stabilizers were tried and they were 2 ft. long each with 2-7/8 in. API regular threaded connections. The 4 straight flutes, or flights, on each stabilizer were originally 3-15/16 in. OD but had to be ground to 3-1/2 in. because of undersize hole made by percussion tool bits. An in-hole motor was used for a short test. The latter test was inconclusive but did point to some consideration for future directional work.

A gasoline powered hoist was provided with 1500 ft. of 1/8 in. wire rope. This was to be used with wire line diamond core drilling but this test was abandoned early because of slow drilling rates of diamond bits, in comparison to percussion drills, as well as an apparent potentially high bit cost per foot of hole for diamonds. It appeared that this bit cost in HSR might be several dollars per foot.

The miscellaneous tools used with the drill rod included the wire line core barrel, an overshot, a swivel for horizontal wire line use, fishing taps, subs and special pipe wrenches. As a result of these tests wire line equipment including overshot and special swivels would not be bought for the future. The most simple core barrel is adequate because of the success of innovations in this test in rapid rod handling.

The most useful instruments for data were conventional pressure gauges, measuring tapes, and watches. Some attempt was made to use more advance recording instruments and with some success. The higher rotary speeds were registered with a magnetic pickup from a gear's teeth. This instrument sent an electric signal to a recorder. This same system was tried for penetration rate but was not effective for that. A three pen circular wind-up chart instrument was used to record 3 pressures. One is pressure for thrust computation, another is for hydraulics to rotary motors for the drill and the extractor, and pressure of water used for diamond drilling circulation. Recorders were very troublesome. These tests showed that it would be better to invest in good direct reading pressure gauges. It was found that many pressure gauges were not reliable for extended rugged service. Fluid flow instruments were installed on the water pump and the hydraulic system. Both were useful but after it was suspected of contributing to the oil overheating, the one on the hydraulic system was removed. In an operation such as this the water flow can be measured by catching it in a container in a measured time, if there is no foam.

5.3 Test Sites

After a cursory examination of the country the search for test sites centered in the California area and in the Maryland-Virginia-West Virginia area. Very generous assistance was offered by quarry operators in both areas.

Three sites were chosen in California because they had rock strength in the range needed and the availability of a working site at the time it was needed. They would save travel.

The first site was in the granite quarry of The Granite Rock Company of Watsonville, California. The quarry is near Watsonville at the town of Aromas. The site is about 80 miles south of San Francisco. The granite rock at Aromas is 26,000 psi compressive strength. The quarry has been in operation for over 70 years and has been benched. The bottom floor of the circular pit is about 170 ft. below the original surface. The quarry's proximity to the San Andreas fault has resulted in fracturing. The test site represented a "bad ground" type of hard rock tunnel situation,because of this and because of the depth below the water table. It was an excellent site for assembling the equipment and making preliminary tests on the different drilling methods because of the good plant facilities.

The second site chosen was at Kaiser Refractories Natividad California plant near Salinas which was 15 miles southeast of the first site at Aromas. The Natividad rock is dolomite of 15,000 psi compressive strength. It was a very good site for determining drilling rates and performance in this kind of nonabraisive MSR. As will be explained it also was a good site to try out some schemes for overcoming lost circulation.

The third site was chosen at the J.B. Stringfellow Company's granite quarry at Rubidouex near Riverside, California. The Riverside rock is 20,000 to 26,000 psi rock. It is very massive and abraisive. Most of the production results for HSR discussed in Section 6 were achieved at this Riverside site. The equipment was stored at Riverside at the conclusion of the test.

6.0 RESULTS

The time of each two foot strokes was recorded. This was for a total of 2230 ft. of drilling at three sites. The deepest hole was 864 ft. During the start of each test, the drilling time per inch of penetration was recorded for detailed analysis but for the most part it was found that nothing significant would be missed by timing only two foot strokes. All delays were timed and their causes were noted.

Drilling parameters were changed in an effort to achieve the optimum conditions for each drilling method. An analysis has been made of these drilling data. It is believed that a creditable projection of possible, or ultimate, production rates are made with these data as a basis.

A drilling crew will drill about 7 hours per eight hour shift. At least one hour will be used in lubricating and other routine-preventative maintenance operations at the beginning and end of each shift. One or two minutes will be used with each stroke of the drill to disengage, retract, and reingage the automatic chuck, and occasionally to blow the hole. If the hole is kept in good shape (or level) one minute will be enough, but 1.5 minutes are added to each stroke in this analysis.

The principal drilling method proposed is the down-hole percussion drill. This method will make about 98% of the hole with the rest being made by diamond bits to get cores. The smaller diameter diamond bit hole is subsequently reamed to full diameter by the percussion drill so, in effect, the percussive drill must make all of the hole.

6.1 Percussion Drill - High Strength Rock

Production in high strength rock (HSR) can be projected from the data taken at Riverside. These data are summarized in Table 6.1. This Table shows the instantaneous penetration rates in feet per hour with daily averages. For example in hole No. 1 on the first day there were 52 feet drilled and data taken so that the 31.5 fph represents an average of 26 two foot strokes. Likewise on the next day's drilling from 52 to 170 ft., the penetration rate was 36.8 fph and this 118 foot interval provides an average of 59 strokes of two feet each.

These tests showed that production drilling is more sensitive to a percussion bit's condition than had been expected. The bits with sintered tungsten carbides with ovoid ends slow down as those inserts wear flat. On a production job it may be desirable and economical to regrind these inserts to maintain a rather well rounded end on the inserts.

Bit condition in deep holes has an indirect but pronounced effect on production as was found on these tests in HSR. It has now been determined that it may be normal in HSR to expect something less than 600 ft. before dulling with a new percussion bit. The last 20% of the hole made by such a bit, or about the last 100 ft., may be undersized

HIGH STRENGTH ROCK - DRILLING DATA

AVERAGE PENETRATION RATES - FEET PER HOUR

HOLE NO. 1		HOLE NO. 2	
To Depth Ft.	FPH	To Depth Ft.	FPH
52	31.5	52	25.1*
170	36.8	160	19.0
192	48.5	249	17.65
233	26.7	258	14.0
244	46.0	302	13.2
270	28.9	310	9.0
338	26.7	368	13.6
420	28.6	416	11.4
499	18.8	476	16.7
560	22.6*	542	13.3
588	17.0	568	25.6*
606	16.6	644	19.8
652	14.3	710	13.5
708	14.2	758	12.9
750	8.6	790	7.0
		820	11.1
		862	7.22

Note 1: First 542 ft. of Hole 2 was 4.5 in. diameter all other runs were 4 in.

Note 2: Both holes started dipping at 200 ft. and were dipping baldy at 600 ft.

Note 3: Asterisk indicates new bit.*

Note 4: These data are from Stringfellow Quarry - Riverside, California.

TABLE 6.1

due to worn gage so that a bit of the same size to follow it would be squeezed and damaged in reaming this section. The best solution, therefore, is to drill the first part of the hole with the next larger sized bit assuming that in a near dull condition it still will be large enough to drill a hole to clear the smaller bit. The main disadvantage to this is that the larger bit for various reasons will drill slower but the rate should still be fast enough to meet the research goals. The larger bit introduces other difficulties of keeping the hole straight and clean, but this change of bit size is a traditional practice in all deep hole drilling.

Anticipated production in a 4-1/2 in. hole is about 80% of that of a 4 in. hole when both bits are new. As they become dull the comparison becomes even less favorable to the larger bit as a fairly dulled 4-1/2 in. bit may provide only half the penetration rate of a similarly dulled 4 in. bit. Still it is necessary to use the larger bit to drill the first part of the hole to prevent damage to that bit which must follow it and finish the second part of the hole. Thus a price in production must be paid for bit dulling and therefore considerable data were taken on this subject of bit condition.

In production some of the reasons for reduced performance of the larger 4-1/2 in. bit are that it cuts about one fourth more hole than the 4 in. bit. Future tests with larger drill rods may overcome some of this disadvantage as it would maintain the air velocity in the larger hole close to that which was obtained in the 4 in. size.

It is not believed that the production data beyond 250 ft. on Table 6.1 can be used for reliable forecasts of drilling performance. Hole number two, particularly, started dipping at that point and for the last 100 ft. was going down at an angle from the horizontal of over 20 degrees. It probably requires considerably more air to transport cuttings from a hole that is dipping 10 degress or more than one that is flat. This may be especially true in a hole that is making some water which these holes were doing. Most drill holes will make water. There appears to be less hole cleaning problems in holes that are absolutely vertical or nearly vertical which can be cleaned with about one-half the velocity needed for horizontal holes. It appears that even larger volumes or velocities of fluids are required when the holes are between 20 degrees and 80 degrees from the horizontal. This would be an interesting and worthwhile research subject.

It appears from the data that instantaneous penetration rates can be projected for the life of the bit of 30 feet per hour for a 4 in. bit and 17 fph for a 4-1/2 in. bit. This means that each foot of drilling requires on bottom drilling time of 2 mins. for the small hole and 3.53 mins for the 4-1/2 in. diam. To compute the two ft. stroke time, these foot time estimates must be doubled for two ft. and one must add 1-1/2 mins. to each such stroke for retracting, setting chucks and blowing the hole. The two foot stroke times then become:

A. 4 inch hole = 5.5 mins.

B. 4-1/2 inch hole = 8.56 mins.

Based on A and B above the net production rate while drilling with the 4 in. bit is 21.82 fph and for the 4-1/2 in. bit it is 14.02 fph, as was explained above both must be used in deep hole drilling.

Four hundred and eighty mins.per shift, less 60 mins. for servicing, leaves 420 mins. for drilling. It is expected that in HSR two cores, one foot long each, will be taken each shift and these will require one hr. each for trip time and drilling, as will be explained.

A test of the extractor on July 17th showed that it can handle the 1000 ft. of pipe and run it in and out of the hole at the rate of 100 ft. in 27 seconds. Thus the design condition was met when the hole is kept level and clean. Trip time to put on and take off the core barrel should not require more than 10 mins. both ways at the deepest point. The average travel time for 1000 ft. holes will be 5 mins.

A core taken on July 14th at 540 ft. is representative of what can be expected in coring HSR when all systems are in good shape. It took 19 mins. to drill two ft. or 6.3 fph. These tests showed that the greatest time requirement in coring may be that for pumping the system full of water and blowing the water out of the hole to return to percussion drilling. The NX casing used as ground storage is 3-3/16 ID or 7.976 sq ins. so that to fill 1000 ft. of it requires 416 gals. That much water is required plus the hole requirements of 76 gals per 100 ft. of 4-1/2 in. hole and the 4 in. hole requires 65 gals per 100 ft. The requirements are going to be between 500 and 1100 gals depending on hole size and depth. Pumping water in and out is going to average about 20 mins. per trip.

The average coring time then should be:

Changing tools	15 mins.
Rod travel time 500 ft. in and out	5 mins.
Drilling one foot	10 mins.
Cycling water in and out of system	20 mins.
Total time per core	50 mins.

Coring should be about 10 mins. less than this for very shallow holes and probably will be 20 mins. more as hole approaches 1000 ft. The one hr per core, or two hrs per shift for 2 cores, seems valid. The production drilling time for percussion drills appears to be 480 mins.per shift less 60 mins. for servicing and less 120 mins. for coring or a net of 300 mins. or 5 hrs. This means that the 4 in. hole should advance 109 ft. per shift and the 4-1/2 in. at 70 ft. per shift.

The goal of this program was to develop a system for HSR that would drill 90 ft. per shift taking two cores. It appears that this has been achieved but the hole's direction problem must be solved before it will be usable beyond about 500 ft. It is believed that this direction problem can be solved. Assuming bit performance matching that at Riverside, a program could be used where a 4-1/2 inch bit would drill the first 400 ft. and the last 600 ft. would be 4 inches. The average drilling production per shift then would be 93.4 ft.

Percussion drill penetration rates in both 4 inch and 4-1/2 inch sizes can be increased by using 200 psi air but that is expensive and no rental units are available in this area to conduct tests. It is also possible that, by experimenting with different bits, a bit design will be found which will make 1000 ft. of hole and then the higher production of the 4 inch size can be realized for all of the hole. Other bit designs also may provide faster instantaneous drilling rates. A higher volume water pump may be used to reduce the hole filling time.

6.2 Percussion Drill - Moderate Strength Rock

Production rates for moderate strength rock can be projected using the same techniques as were used for HSR in Section 6.1. The drilling data taken at Natividad will serve as the basis.

In MSR perhaps, 3 cores will be required per shift. Each will take almost as much time as will be used for coring HSR because the drilling time is not a major factor. Lost time to percussion drills then becomes 3 hours for coring and one hour for rig maintenance or servicing, or 4 hours total per shift.

An analysis of performance at Natividad shown in Table 6.2 indicates that 75 fph might be expected, when the hole is kept flat and clean. This is 1.25 fpm so that a two ft. stroke will require 1.6 minutes drilling plus 1.5 minutes to reset and blow the hole, or 3.1 minutes total for two ft. This figures at a production drilling rate of 38.7 fph. There will be 4 hours available per shift for drilling full hole so the system should produce 154.8 ft. which is about 14ft. less than the goal of 168 ft. per shift established at the beginning of the project. It is believed that there is enough slack in the three hours lost time allowed for coring and servicing to achieve the 168 ft. per shift goal. There is also a good possibility of increasing the drilling rate as methods were improved at Riverside. Even at the current rate only 1/2 half hour per shift of drilling needs to be gained which may be possible by simply increasing the water pump capacity.

The runs with the diamond core bits at Natividad are not dependable. The drill would not rotate at more than 150 rpm most of the time and at this rotary rate the penetration was 6 fph. It should be at least double that in that kind of rock and undoubtably will be on future runs at 400 rpm or more.

MODERATE STRENGTH ROCK (MSR) DRILLING DATA

AVERAGE PENETRATION RATE - FEET PER HOUR

To Depth Feet	FPH
13	
26	
94	75.1*
146	63.0*
285	75.8
311	75.2
337	160
487	68.0**
508	56.8
570	18.7***

* These two runs were with a larger percussion tool and 5-1/4 inch bit. Other runs were with the 3-1/2 inch diameter tool and a 4 inch bit.

** Hole is beginning to dip badly at this point.

*** This bad run was a result of a drilling machine problem

NOTE: Tests were in Dolomite at Kaisers' Natividad Plant.

TABLE 6.2

7.0 TECHNICAL PROBLEMS

7.1 Hole Direction

Hole direction control seems to be one of the most serious unsolved problems. Holes have been surveyed and it appears that they remain quite straight for 200 to 300 ft. At about 250 ft. horizontal holes start to dip and veer to the right.

The dipping becomes quite severe and seems to accelerate as depth progresses. The critical space where the deviation is experienced in probe hole work is between 400 and 700 ft. As a rule of thumb the dip of holes is about 10 ft. per hundred ft. in this range if nothing is done to prevent it as is indicated in survey data in Table 7.1.

The lateral deviation is a less serious problem and it appears to progress less than 3 in. per 100 ft. usually to the right or in the direction of rotation. All of these evaluations are based on drilling a massive and homogeneous rock. A bedded or schistostic formation with planes at an angle to the hole direction or formations with varying strength naturally would add to the severity in the change in direction and perhaps provide different directional positioning.

It is quite evident that a slender drill stem, in relation to the hole diameter, is quite serious in causing hole deviation particularly when the thrust must be applied to the rear end of such a drill rod. Naturally gravity tends to draw the hole down. Rotation of the drill rod will tend to change the course of the hole in the direction of the rotation.

7.2 Circulation Problems

The loss of flushing fluid, water or air, into the formation has proven to be a more serious problem than was anticipated. At all three drilling sites some loss was discovered at different times. The loss of air circulation at Aromas was quite dramatic. It is strange that at Aromas water circulation could be maintained in air loss situations while at Natividad, in a water loss situation air returns were easier to maintain. At Riverside there was occasional loss of circulation of air and water, but neither was very serious. There is much to be learned about this problem.

When the severity of this lost circulation problem became apparent the work plan was modified to place more emphasis on this and delete other testing now deemed unnecessary. Common lost circulation materials used by well drillers includes bran (as is fed to livestock), sawdust and rice hulls. There are also commercial products prepared by the drilling mud companies. Bran was tried and did no good.

A scheme was tried at Natividad which seemed to

HOLE VERTICAL DEVIATION - FEET

Depth Hole	HOLE NUMBER 1	2	3
100	2.07	0.22	2.37
200	15.23	1.85	8.70
300	30.11	2.51	17.41
400	47.26	3.49	31.96
500	66.66	13.50	55.91
570	82.92		-
600	-	28.06	-
700	-	50.98	-
748	-	63.40	-
800	-	-	-

NOTE: Hole one is at Natividad. Holes two and three are holes one and two at Riverside.

Table 7.1

work quite well. So far as is known this technique, as done precisely here, was a unique development of this program and it's success was surprising. Several slugs of cement grout were pumped into a 570 ft. deep hole into which all fluid formerly pumped had been lost. These slugs of grout were alternated with slugs of water. Approximately 1-1/2 cu. yds. of grout were pumped in. It was a very "soupy" mix of approximately 7 cu. ft. of sand and 20 cu. ft. of cement to the cu.yd. of grout. It was pumped through a 420 ft. long 2 in. grout pipe so that the end of the pipe was 150 ft. from the inner end of the sloping hole. The grout was pumped in three, approximately equal, slugs. In order to clean the grout pipe between slugs, water was pumped through. Evidently this alternating of water and grout mixture plastered the wall of the hole. The grout remaining in the hole was allowed to set over a weekend. A diamond bit probed the hole on Monday and found the grout plug at 405 ft. or 15 ft. in back of the former location of the end of the grout pipe. After redrilling, circulation was regained all the way.

It was found that in diamond drilling 20 gpm of water at about 60 psi is adequate to clean a "B" size hole.

As has been mentioned, air flows of 300, 450 and 600 cfm were tried for the percussive drill. Very little difference could be observed in penetration rate or hole cleaning between 300 and 450 cfm and there were frequent hung pipes at 300 cfm indicating insufficient circulation. 600 cfm was much better. It appears that a horizontal hole with a rotating drill rod will require 7,000 fpm air velocity in the annulus.

Air required to clean the hole can be determined as follows:

$$V = 38.16\,(D^2 - d^2)$$

Where: V = Volume of free air in cfm
D = Diameter of hole in inches
d = Outer diameter of drill rod in inches

Table 7.2 gives air requirements for several combinations of hole and drill pipe size. It should be noted that the smallest down hole hammer requires 300 cfm of air so this is a minimum. It should also be noted that, as of now, there is no automatic chuck for drill rods larger than the "N" size or 2-3/4 in. If some "H" size (3-1/2 in.) or larger rod is used as a stabilizer it must be put in or taken off between the drill and the mouth of the hole. It was mentioned earlier that air volume, or velocity requirements, increase rapidly as holes dip. Much of the decrease in production on these tests at great depth was due to difficulty in cleaning the holes which often dipped more than 20 degrees from the horizontal.

7.3 Overheating Hydraulic Systems

Traditionally most drilling systems such as this have been used with mechanical drives, except for thrust mechanisms

FREE AIR CFM FOR 7,000 FPM VELOCITY

	DRILL ROD		HOLE DIAMETER INCHES		
MANUFACTURER	TYPE	O.D.	4	4.5	5
Longyear	BQ	2-3/16	427	589	771
Sprague and Henwood	BX	2-1/4	417	579	761
Longyear	NQ	2-3/4	322	484	665
Sprague and Henwood	NX	2-13/16	308	470	652
All Makes	HW	3-1/2	143	305	486

AIR REQUIREMENTS

TABLE 7.2

because hydraulic systems are less efficient. The drilling systems proposed for the ultimate drill probably will demand a hydraulic system because of space limitations as hydraulic drives can be made smaller than a mechanical drive for the same hp and the power unit for it can be isolated.

It was found in these tests that hydraulic systems work quite well in a drilling operation. At the same time it was found that the oil in the hydraulic systems overheated quite badly. This overheating was a very serious detriment to all of these tests. Hours were lost each day and it is estimated that the efficiency during the operation was decreased by at least 25%. Conversations are being held with manufacturers to overcome this problem. Some improvement may come from a change in motor or pump type.

A 55 gal oil drum was added as a supplemental reservoir to the drill for cooling as shown in Figure 7.1 but it did not solve the problem. Several restrictive small pipes and a flow meter were removed with only marginal results. Additional work must be done on pumps and circuits to solve this problem and a heat exchanger or radiator will be added for future tests.

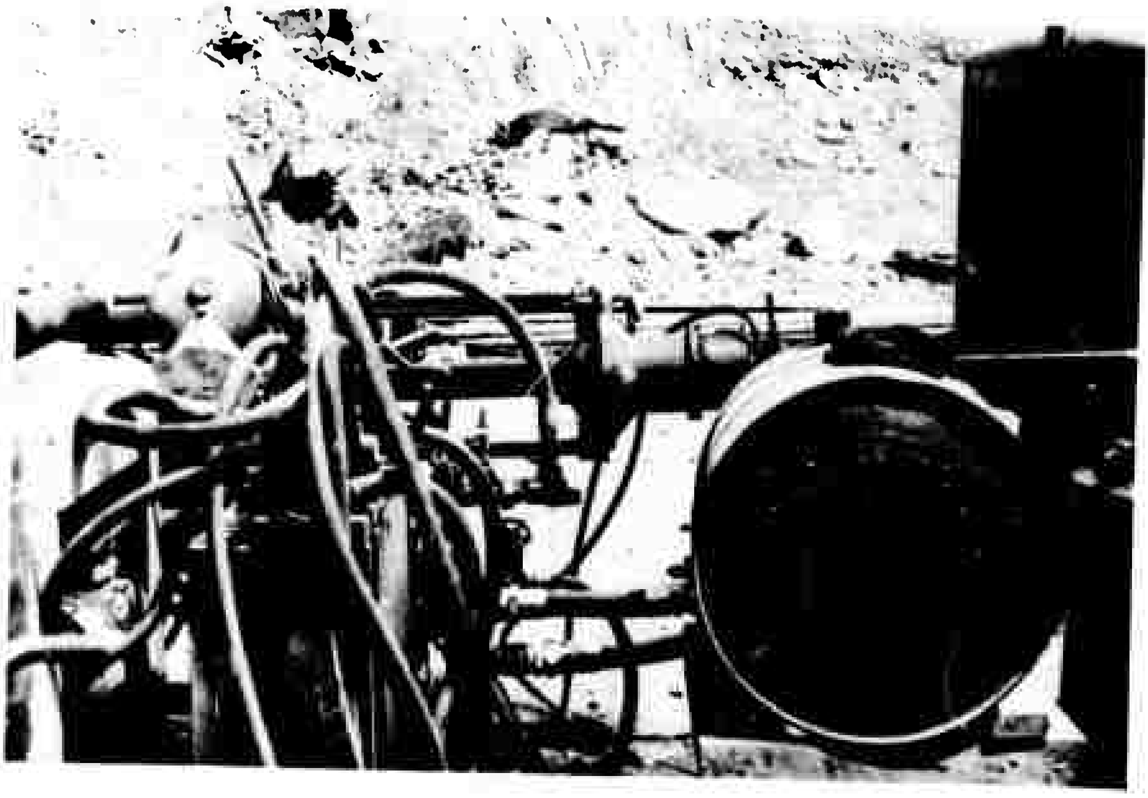
7.4 Bit Dulling

Bit dulling in MSR is not a very serious problem. It is a tremendous problem, but not an insurmountable one, for most of the drilling in HSR as was discussed in Section 6.2 on production.

It has been pointed out that sufficient thrust can not be applied to rolling cutter bits. These bits, therefore, can be expected to wear out rapidly in this service and they do. Manufacturers of rolling cutter bits generally recognize their limitations in that it is difficult to make such a bit for hard abraisive rock in diameters of less than 5 inches. With this design limitation and the lack of ability of the drilling method to apply appropriate thrust, it is not surprising that a new rolling cutter bit failed in HSR after a few inches of poor performance.

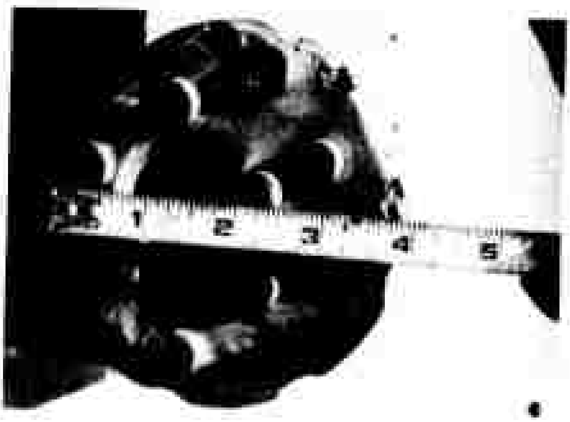
Diamond bit life in HSR was also a disappointment although it is recognized that diamond bits must be used where a solid and undistrubed sample is to be taken. There had been some feeling prior to this field testing that diamond coring might be used for all the drilling. The decision against exclusive diamond drilling resulted primarily from the method's slow penetration rate. There also is the very serious problem that diamond bits wear out in this kind of service in 50 to 100 ft. in HSR. This means a bit cost of two to three dollars or more per ft. in this rock which would be unacceptably high in most circumstances.

The solid head percussion bits did very well in bit life in MSR but did not get as many feet as had been expected in HSR. In pre-test studies it had been estimated that such a solid head bit would make at least 1000 ft. of hole. As tests progressed these predictions were borne out in MSR, but in HSR the bits dulled at about 500 ft. This meant



ADDED 55 GAL. OIL RESERVOIR

FIG. 7.1



WORN 4½ INCH BIT

FIG. 7.2

that it would be necessary to plan on the use of two bits for 1000 ft. deep holes as was discussed in the production section.

It was also discovered in these tests that loss of gage on solid head percussion bits in deep holes will be a problem. Figure 7.2 shows a completely dulled 4-1/2 in. bit which had been worn to about 4 ins. Perhaps until it lost its last one or two gage inserts at the very end of it's run, it was drilling about a 4-1/4 in. hole. This loss of gage introduces several new problems besides the fact that two different bit sizes must be used as these bits don't ream well. The optimum drill rod diameter then becomes a compromise generally dictated by the smaller or second bit. This is unfortunate because the larger hole is harder to drill. Also the larger the bit is, in relation to the drill rod, the greater is the tendency for the hole to go down or dip.

Another unfortunate result of gage loss for this operation is that some of the hole direction techniques won't be as effective as they might otherwise be. Many of these techniques have been developed for rolling cutter bits. One of the good features of these rolling cutter bits is that they hold gage better than a solid percussion bit. This is because they have more gage to wear on each of three cones. Rolling Cutter bits also are inherently designed with the cones mounted on a pin, or head bearing race, which is sloped upward to the gage from the center of the hole. Thus as they wear there is a tendency for the cones to be forced upwards and out to gage. Much of the hole straightening science has been developed for oil well drilling where these bits predominate. Many of the techniques, therefore, depend on a full size hole.

The bit dulling process is extremely important to understanding this method of drilling. Figures 7.3, 7.4 and 7.5 show the progressive stages of bit wear at the Stringfellow Quarry at Riverside. The first 4 in. bit had made 172 ft. of granite hole at Aromas and 492 ft. of dolomite at Natividad before being used at Riverside. The second 4 in. bit made only 158 ft. but was probably damaged by being forced to ream a tight hole.

The stabilizers that had been provided for this test were selected on the basis of rolling cutter bit practice. Their performance is related to bit dulling so they are shown here. These stabilizers are described in Section 5 and are shown in Figure 7.6. They were made with the 4 flutes 3-15/16 in. OD. This is rather tight but would fit into a hole made by a 4 in. rolling cutter bit. They would not go into any hole made by a 4 in. percussion bit dulled as shown in this discussion and had to be ground to 3-1/2 in.

7.5 Equipment Positioning

Equipment positioning and anchoring on the quarry floor is quite difficult in tests such as these. The ultimate tools underground may have more problems of positioning because of space limitations and the need to coordinate with other equipment. Anchoring the tools underground on the other hand should be somewhat easier in some respects as jacks can be applied against the top and bottom of the tunnel.

492 FEET

4-INCH BIT NUMBER ONE

590 FEET

4-INCH BIT NUMBER ONE

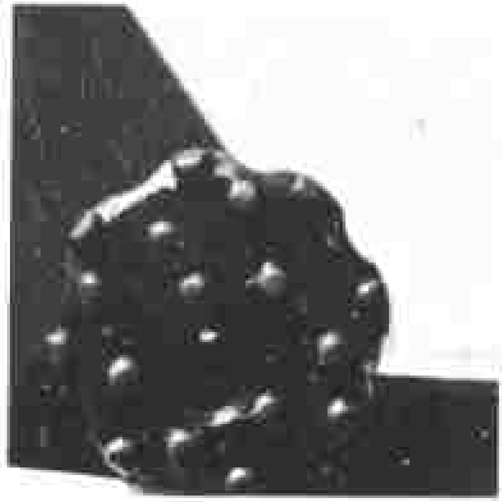
158 FEET

4-INCH BIT NUMBER TWO

BITS ONE AND TWO
RIVERSIDE QUARRY

FIG. 7.3

249 FEET



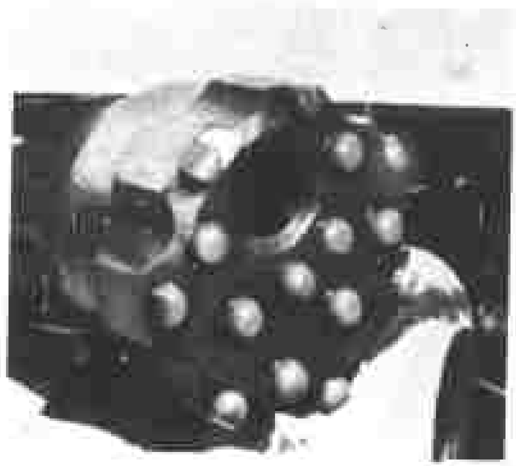
416 FEET

540 FEET

4½ INCH BIT NUMBER THREE
RIVERSIDE QUARRY

FIG. 7.4

126 FEET

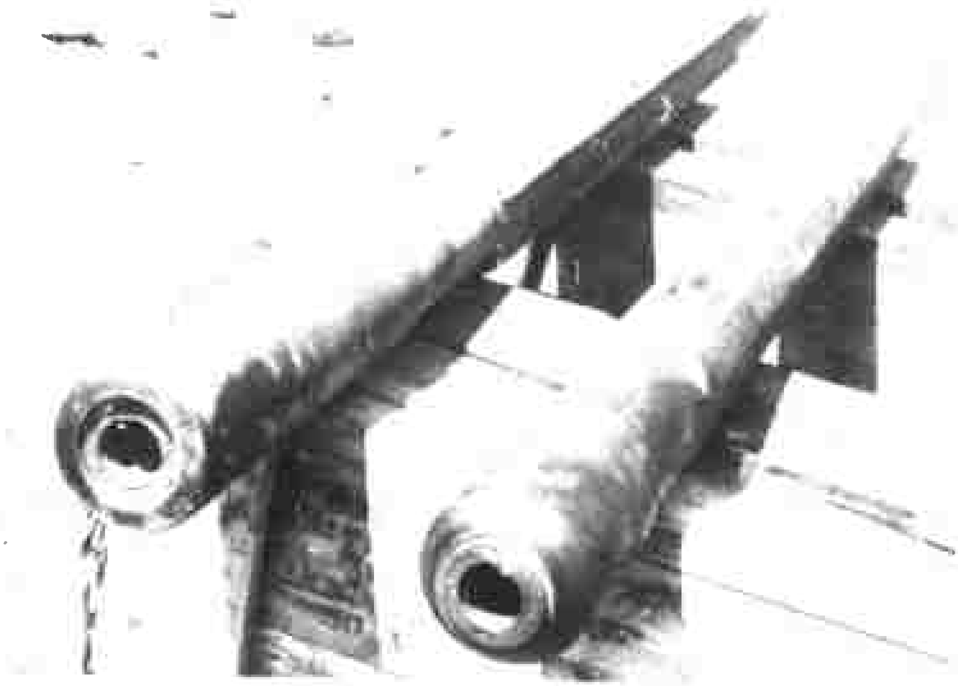


248 FEET

324 FEET

FOUR INCH BIT NUMBER FOUR
RIVERSIDE

FIG. 7.5



TWO 3½ INCH DIAMETER STABILIZERS
SHOWING CONNECTION FAILURE

FIG. 7.6

Alignment of equipment is quite critical. The rod extractor must be in nearly perfect alignment with the drill hole and drill. See Figure 7.7. It was found during these tests that mechanical anchors, such as roof bolts, which depend on an expansion of their body or a shell in the hole to grip the rock are not satisfactory. In most quarries the rather high explosive charge has been shot near the floor and has shattered the rock to a few feet of depth. The best anchors for quarry work proved to be a loop of wire rope grouted into a drilled hole. One of these with a chain come-along can be seen at the corner of the drill in the center of Figure 7.7.

One of the alignment problems was solved by mounting the rod extractor on an extension of the base of the drill.

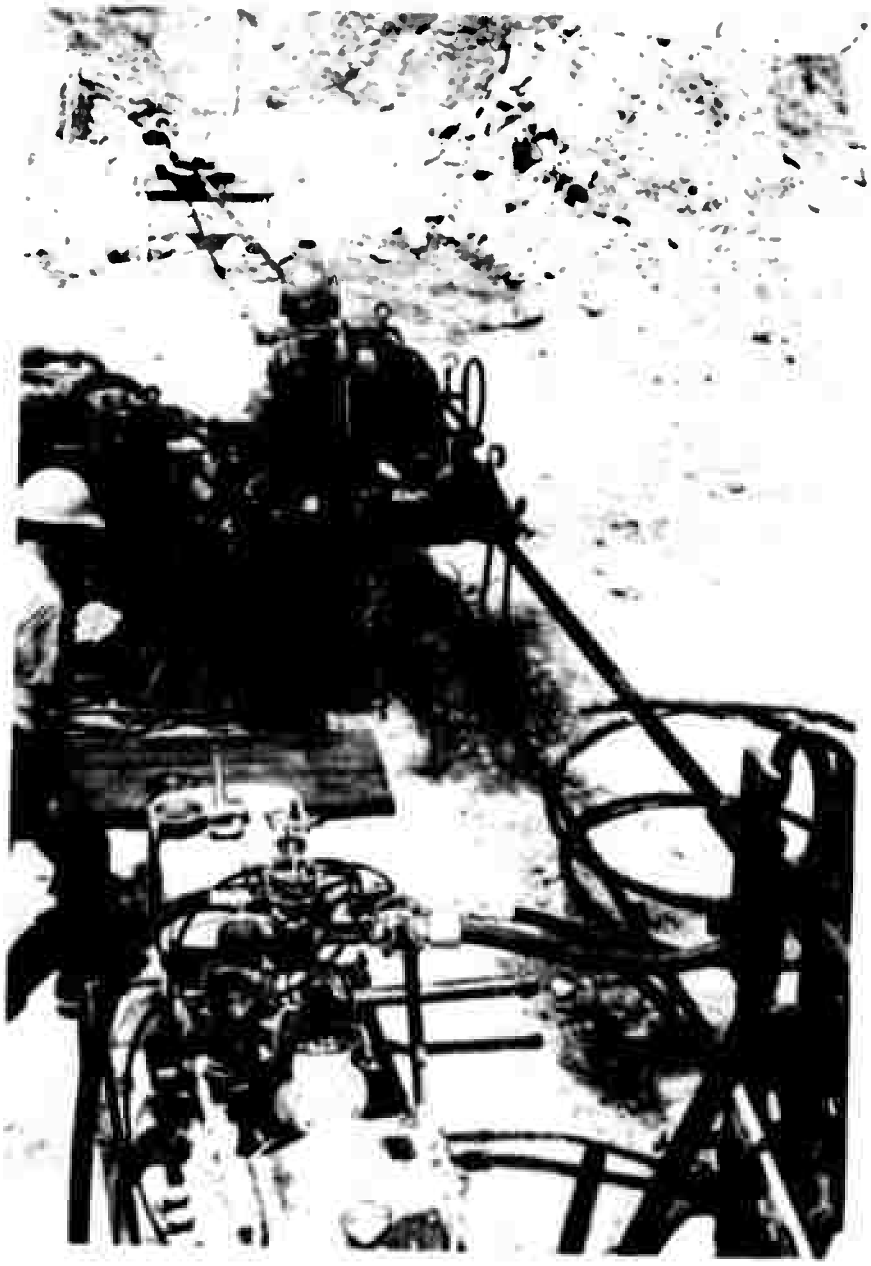
Figure 7.7 also shows that some distance is required between the extractor and the mouth of the hole to remove special tools such as stabilizers, core barrels, percussion tools, etc. This must be at least 20 ft. and holding this unconfined rod from bending is difficult for high thrust tools, such as rolling cutter bits.

7.6 Drill Rod Problems

Drill rod problems included unscrewing of sections in the storage pipe behind the drill as well as a series of twist offs or pipe failures in the hole. It had been anticipated that the rod in the storage pipe might unscrew because the torsional forces were in the direction to cause it. Several of the new epoxies were tried and for the most part were unsuccessful. The best adhesive to put on the threads was found to be a commercial resin. This costs only about $5.00 per gal and can be bought in any large paint store as one of it's uses is to apply fiber glass layers to wood. It does have a catylist that must be mixed in quantities so that no more is mixed than can be used in one or two hours. When a rod separation does occur in the storage pipe it is easy to take the rear pipe off and push the disconnected section out the back of the storage pipe with the rod extractor. It can then be dragged to the front end and inserted and reconnected there.

Four drill rod failures occurred in the hole being drilled and all happened in the last two months at Riverside. Two of the pipe failures were at the connections near the tool. Two were at an intermediate spot in the string. One broken pin can be seen in Figure 7.6. These were retrieved by a fishing tap shown in Figure 7.8. The first failure was in a 4-1/2 inch hole and it was necessary to make a 3-15/16 inch centralizer shown in Figure 7.9. This sleeve raised the tap so that it would enter the fish which was one of the tool sub failures and presented a high center.

The third failure was in the drill rod 180 ft. from the bottom or end of 864 ft. deep hole number 2 at Riverside. The fourth and last failure was after this 180 ft. was caught on a fishing tap. It was necessary to get a second fishing tool to retrieve 350 ft. of rod including the first fishing tool, the percussion tool and a 4 in. bit. No



EQUIPMENT ALIGNMENT
RIVERSIDE

FIG. 7.7

FISHING TAP AND FAILURE

FIG. 7.8

FISHING TAP CENTRALIZER

FIG. 7.9

centralizer is needed for catching the thin wall drill rod in a flat hole.

An impending trouble spot on the drill rod was observed but no pipe failure occurred there. Figure 7.10 shows an unusal groove developing just out-by the shoulder between the sub connecting drill rod to the larger tools on the forward end. At this point it is not known whether that groove is ground there by material trapped at this point or by some strange cavitation process, or something else. Figure 7.9 and 7.10 show another interesting development of the test and that is the rear reaming teeth which were field installed by torch applied hard metal on this shoulder. In horizontal drilling there is a strong tendency for the fluid to flow on top and leave cuttings on bottom. These teeth gave the capability of drilling rearwardly through such debris which otherwise was piled up by this shoulder and caused several cases of stuck pipe.

Some of the early percussion tool failures were attributed to a drill rod condition. At one point at an early test at Aromas, the tool was pulled to be cleaned because of low power. It was found to have metal cuttings as are developed in a machine shop. New rod in the future should be examined internally and perhaps flushed with an abraisive solution such as sandy water circulated for a few hours. It could be that this metal was some of that scoured on the external surface of the drill rod by the automatic chuck while the tools were stuck or when high thrusts were tried on rolling cutter bits, but the metal chips looked more like shop cuttings. The external scouring was rather bad on the packing in the stuffing boxes which otherwise lasted several shifts.

Getting the drill rod free when it became stuck frequently was quite difficult. In some cases when the percussion tool became stuck water could be circulated through it, and the system, to free it. In a very stubborn case fuel oil was pumped and it did not do any good. Commercial detergents were tried and they too failed to free the tool. Finally two special compounds for stuck drill rod were obtained. These were Condet and Quik-Trol. Four gallons of Condet were mixed with water in a 55 gallon drum on June 26th and pumped into the hole at Riverside. This was followed by 55 gallons of water. This was followed by a mixture of two pounds of Quik-Trol powder dissolved in a gallon of diesel fuel which in turn was mixed with water in a 55 gallon drum and followed by 55 gals of water. This was left in the hole overnight and the tools were free the next morning in the first ten minutes.

WORN GROOVE IN PIPE

FIG. 7.10

8.0 FURTHER RESEARCH INDICATED

The major future research effort in this field must be in an underground test preferably in a tunnel being driven by a boring machine. Data on the tests to date, however, indicate that further additional surface or quarry drilling is desirable, if not essential, before going underground.

The main reason for additional surface tests is to develop methods to prevent hole dipping as described in 7.1. These efforts will include:

1. Packing the hole for 50 to 100 ft. with a drill rod about 1/2 in. smaller than the hole being drilled to provide rod stiffness at this critical zone.

2. Use short (6 to 12 in.) stabilizers about the diameter of the hole being drilled spaced with one as close to the bit as possible and one 20 to 30 ft. away. This method wedges the bit in an upward attitude and was used by the British in methane drainage in coal in the 1950's. (3) and (5). It is not known how it will work in hard rock.

3. The use of rubber or resilient stabilizers should be tried.

4. Rental and use by test crew of single shot surveying instrument so that corrective measures can be tried before severe deviation has occurred. Such an instrument was rented for about $250 per month at the end of the current tests and worked quite well. Twenty ft. of aluminum drill rods had been purchased but 10 more ft. should be bought.

5. Consideration should be given whipstocks and two diamond bits. One small B diameter bit (2.36 ins.) can be kicked off in the desired direction for about one foot. This would be followed by a special (3.50 in.) diamond bit with a pilot to ream this hole. The worn 4 in. percussion bit should follow this deflected one foot long hole.

The additional quarry tests also will provide a means to get the electrical system working properly. This system will be needed in the underground tests to follow. Arrangements must be made with a contractor and/or owner for test underground. It may be that this test will be in a mine rather than in a public works tunnel.

The test drilling in such a working site must be at the convenience of the owner and/or contractor. Plans, therefore, cannot be made at this point as to whether the drilling will be done from an alcove or through a window in the tunnel boring machine head. For test purposes the latter may be desirable but there will be some lost time as it would have to be done on a weekend or on off shifts. Hopefully by that time faster drilling rates and drill dependability will have been achieved so that not more than two or three weekends would be required.

The underground tests would attempt to probe and sample 1000 ft. ahead of the TBM but might be limited to about 500 ft. if the only site available is HSR and the work has to be done on weekends. Detailed plans or goals on depth can be made as the project progresses.

Lost circulation is a probability in a tunnel being driven. The cement grout scheme should be tried again, if time permits further research on this, at a surface site where the condition exists. A commercial sealing product such as Hy Seal also should be tried.

The effects should be determined of using a radiator or a heat sink to cool the hydraulic oil. Use of larger percussion drills for 5 or 5-1/2 in. diameter holes should be tried with rental tools in HSR. A short run in the quarry with 900 CFM of air should be tried.

For economy as much of the existing tools should be used as can be used where results of the tests won't be affected too severely. The rotary drill and pump can be modified to work from a hydraulic power package for the drill and a direct electric motor drive for the latter. As it is now, the extractor can be driven by the drill power unit.

9.0 GOVERNMENT AGENCY IMPLICATIONS

The public of the United States probably is the biggest single purchaser of tunnels in MSR and HSR, particularly in rock where geological prediction is difficult. Some of the mining companies drive many miles of rock tunnels per year and the miles of privately purchased tunnels aggregate probably exceeds that for public works. Generally these private companies have done much more exploration drilling and are in rock in which they have had experience. As a consequence in some cases they won't need a probe. In other cases where they are following a meandering ore body the probe may be very important. Most public works tunnels, particularly those not in urban areas, must be driven with less knowledge. The benefits that will accrue to private companys will benefit the public through greater safety and better utilization of natural resources.

Public works tunnels in the United States often must be started with a minimum of core drilling pre-bid planning. A method to predict geological conditions therefore would remove some of the financial and time risks to the contractor and lead to a savings to the government, or public, providing more competitive bidding, and make the work safer. It would also reduce the guess work which often leads to costly change of condition claims.

Most public works tunnels in rock are for water, sewer and transportation. The military historically has had an interest in underground excavation. In ancient history tunnels were driven under defense walls of cities. One of the classic battles of the Civil War was the Battle of The Crater at Petersburg, Virginia where Pennsylvania miners drove a tunnel under the Confederate line in an abortive effort to break the line. More recently the military has had some well publicized hardened sites excavated in rock for command operations and for missile silos. It is presumed that other applications are under consideration.

10.0 CONCLUSIONS

A horizontal probe hole drill using a combination of diamond and percussion drilling can be developed to meet the goals of this effort. These goals are to drill 1000 ft. deep at the rate of 90 ft. per shift in high strength rock and 168 ft. per shift in moderately strong rock. This will be achieved by using down hole percussion drills to obtain instantaneous rates of 30 and 60 fph in the two kinds of rock.

A new combinat ion of some old but unproven ideas of pipe storage behind a drill (6) and new ideas of fluid circulation into such a system and novel ways of pulling rod in and out of the hole have been made to work. They work with air or water circulation. The powered rod extractor will move 1000 ft. of rod in or out of the hole at 200 fpm.

Hole deviation is going to be one of the more serious problems requiring additional research. The investigating group has an opinion that by stiffening the drill rod and/or by packing the hole with stabilizers at strategic points the problem or declining hole can be overcome. This is an opinion only and additional effort in quarries is required to establish the effectiveness of each idea as well as details such as the position of the strategic points for stabilizers and the shape of stabilizers and/or the nature of the rod stiffeners. This development, when carried to a conclusion, should pay off not only in reduction of accidents but in underground construction costs savings in dollars and in time.

Other specific conclusions of the Test include:

1. The percussion tool must be kept clean internally (this is not too difficult with the protective features provided).

2. Air pressure must be maintained as high as possible and in no case should it fall below 100 psi at the delivery point, or compressor.

3. The hole must be kept flat. There is evidence from these tests that drilling rate decreases about 2% of the initial drilling rate per degree of downward slope of the hole from the horizontal. There is also evidence that if precautions are not taken to prevent it the hole may dip about 5 degrees per 100 ft. after 300 ft. of depth.

4. Drilling will become slower as the bits become dull. Even those bits with cylindrical, sintered-tungsten carbide, inserts, which appear "dull" when new, slow down as the new ovoid shaped ends of the inserts wear flat. From these tests it appears that the decrease in penetration rate from bit dullness is about one half of one percent of the new drilling rate for each per cent of bit dullness. The gradual bit dulling shown pictorially is in Fig. 7.3, 7.4 and 7.5.

5. Hole depth should not affect the penetration rate of down hole percussion drills, because the percussive energy is at the bit, but depth does affect the penetration rate. This is due in part to the fact that the operator loses some control. Running a down hole percussion drill remains somewhat of an art. If enough thrust is not provided, the drilling rate will decline. Too much thrust,or overloading will stall the drill and slow the penetration. The driller knows approximately how much thrust is required (approximately 2000 pounds for the tools used in this test) but the fine adjustment in a narrow range above and below this median is made by sound, feel and drill advance rate. As the hole gets deeper only drill advance rate will be a guide as sound and feel are dampened. This factor of loss of control become significant only after about 100 ft. has been drilled and beyond that point a loss of about 20% of the initial drilling penetration rate can be expected due to control problems.

6. It appears that an annulus velocity in a small flat hole must be 7000 fpm to clean the hole. Future tests may show that a higher velocity is required in special conditions such as in a hole with an in-hole motor in which the rod does not rotate. Such an in-hole motor operation is not planned for the proposed system except possibly for short runs to redirect a hole. This means 600 cfm in a 4 in. hole with "B" rod.

7. Coring will require about one hour per core. The rapid rod extractor, designed and built for this project, reduces the pipe traveling time to less than 10 mins. regardless of depth.

8. 20 hp will run either the rotary drill or the rod extractor but 35 hp must be provided at the power package to achieve this with a hydraulic drive system.

9. Resin sold for applying fiberglass and obtainable in most large paint stores will prevent most cases of rod unscrewing in storage pipes.

10. Fishing for broken rods in the hole, in this kind of operation, is quite easy. In four cases the rods were caught on a fishing tap within about one hour.

11. Slugs of a few cu ft. of very wet sand-cement grout alternated with slugs of water will plug up some lost circulation zones.

12. There are some very good lubricants available commercially as mud additives to free stuck drill rods and a supply

should be kept on hand.

13. Stuffing box maintenance is a very minor problem.

14. Oil heating in the hydraulic system is a very serious problem but hydraulic systems will work and must be used for space considerations.

15. The fairly recently developed hydraulic chucks are excellent time savers and essential to rapid drilling. They are difficult to repair and very sensitive to pipe size and chuck fit.

16. Wire line hoists are not needed.

17. Good conventional instrumentation is essential but recording instruments are not necessary.

18. Surveying instruments are quite easy to operate and interpret.

19. Any drill rod section with a square shoulder should have teeth welded on so it can drill its way through debris which may have settled on the bottom of the hole.

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12.0 ABBREVIATIONS

API	-	American Petroleum Institute
CU.FT.	-	Cubic Feet
CU.YD	-	Cubic Yards
CFM	-	Cubic Feet Per Minute
FPH	-	Feet Per Hour
FPM	-	Feet Per Minute
FT.	-	Feet
GAL	-	Gallons
GPM	-	Gallons Per Minute
HP	-	Horsepower
HSR	-	High Strength Rock (20,000 to 30,000 psi Unconfined Compressive Strength)
MSR	-	Moderate Strength Rock (10,000 to 20,000 psi Unconfined Compressive Strength)
ID	-	Inside Diameter
OD	-	Outside Diameter
IN.	-	Inches
LB	-	Pounds
PHDM	-	Probe Hole Drilling Machines
PSI	-	Pounds Per Square Inch
RPM	-	Revolutions Per Minute
TBM	-	Tunnel Boring Machines
YD.	-	Yards

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